From GOCE to NGGM: Automatic Control Breakthroughs for European future Gravity Missions

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Abstract: After the successful European gravity mission GOCE (Gravity field and steady-state Ocean Circulation Explorer), which provided an unprecedented high resolution static global map of the Earth's gravity field, the European Space Agency has proposed several preparatory studies for a Next Generation Gravity Mission. The NGGM mission objective aims at measuring the temporal variations of the Earth gravity field over a long time span (namely a full solar cycle) with an unprecedented level of accuracy, both in spatial and temporal resolution. The GOCE technological heritage is leveraged as starting point while defining the NGGM future mission concept. Nonetheless, to accomplish its challenging scientific objective, the NGGM mission concept envisages a wide range of innovations, with respect to the past or flying missions, both on technological and automatic control side, as the satellite-to-satellite tracking technology based on laser ranging, and several spacecraft and GNC features. Thus, this paper focuses on the guidance, navigation and control design evolution for the European gravity missions, from GOCE to NGGM design. After recalling the GOCE GNC main design concepts, the paper will describe the most important innovation required by NGGM. Indeed, such a future concept will consist of a two-satellite long-distance loose formation, where each satellite is controlled independently to be drag-free, GOCE-like. The satellite-to-satellite distance variations, encoding gravity anomalies, will be then measured by laser heterodyne interferometry for inter-satellite ranging at 20 nm resolution, or better. Hence, an orbit and formation control is now required to counteract bias and drift of the residual drag-free accelerations, in order to reach a bounded orbit/formation long-term stability. Finally, GOCE control flight results as well as NGGM simulated results, via a high-fidelity simulator, will be provided. These results highlight the GOCE GNC in-flight achievements as well as the NGGM concept validity, showing that the expected control performances are in agreement with the consolidated mission requirements, all over the 10-year mission.

Keywords: Guidance, navigation and control of spacecraft, formation flying, drag-free, pointing, gravity monitoring

1. INTRODUCTION

Automatic control in the field of astronautical engineering has been of outmost importance since the beginning of the space era. In particular the Guidance, Navigation and Control algorithms have become more sophisticated in order to exploit the enhanced performances of the on-board instrumentation, the variety of the progressively available sensors and actuators on the market, and the challenging requirements of the payloads. Not being that critical as per the manned mission (Woods, 2011) in providing reliability and a very low risk all over the mission phases (from launch, to orbit transfer till *rendezvous*), still the control design for scientific and commercial satellites have to ensure the mission goals during all over the nominal (and possibly extended) mission lifetime, with a very high reliability and the minimum intervention from ground. Restricting the field, in modern times, to missions requiring – preferably - ultra low orbits (down to 230 km) for mapping the mean and variable gravity field, peculiar designs and unique challenges can be recognized in the attitude and orbit control systems (AOCS in brief), of the already flown GOCE mission (GOCE URL), and its follow-on mission concept, provisionally called Next Generation Gravity Mission (i.e. NGGM). The observational concept relies on the fact that the Earth gravitational field is produced by the mass of all its parts: hence, it contains information about the morphology and density of the crust and of the interior of our planet, and how the mass distribution changes in time, due to tectonic plates displacement, the rain that fills the river basins, the glaciers formation and melting, the currents that cross the oceans, the atmosphere circulation, and so forth. As a consequence, gravity constrains the motion of the Earth's satellite, both natural and artificial.

Along the paper, the GOCE mission and the NGGM concepts will be presented with a focus on their AOCS design, and with a particular emphasis on the design of the fully-automated "loose" formation control tailored to future gravity missions, unique in its genre for an Earth Observation mission in low orbit.

2. GOCE Mission

2.1 Scientific requirements and in-flight performances

The GOCE design concept emerged gradually, over more than 20 years, from a complex interplay of science drivers, technology needs, and the sometimes tough reminders of technical and programmatic realities.

The scientific objectives of GOCE were the determination of the Earth's steady state gravity field anomalies with an accuracy of $1x10^{-5}$ m/s^2, and the determination of the geoid height with an accuracy between 1 to 2 cm, at length scales down to 100 km. To achieve these scientific objectives, GOCE flew in a Sun-synchronous orbit (96.7° inclination, ascending node at 18.00 h) with an altitude in the range of 250÷280km, and it carried out two measurements: gravity gradients by the Electrostatic Gravity Gradiometer (EGG), and Precise Orbit Determination based on GPS data.

The 1060-kg GOCE spacecraft was launched on 17 March 2009 from Plesetsk on a Rockot launch vehicle.

Altitude and drag compensation of the slender spacecraft with small (1.1 m²) frontal cross section was realised by two ion thrusters (main and redundant) with a force range between ≈1 and 20 mN, operated in closed loop with the payload accelerometers. Three magnetic torquers with fine (≈36 Am²) and coarse (400 Am²) regulation modes provided the attitude control. About 41 kg of xenon and 14 kg of nitrogen made up the propellant allowance for orbit and gradiometer calibration, sufficient for the planned 2.5 years lifetime. The actual mission evolution was vastly different from the worst-case predictions. Solar cycle 24 turned out to produce the lowest maximum ever measured. Thanks to the low density environment and to the conservative pre-launch satellite drag estimation, the entire mission was spent at altitudes lower than the minimum planned before flight, first around 260 km and then reaching 250, 245, 240 and even 230 km in the final months (Fig. 1).

The nominal mission duration was 20 months, whereas the actual lifetime has been of 55 months almost doubling the expected one. Neither orbit raising nor hibernation were necessary and the gradiometer continued taking high-quality readings, unaffected by variations in its dynamical and thermal environment, even when the slowly accumulating mismatch between altitude and inclination brought the mission out of sun-synchronicity, causing longer and longer eclipses. Both temperature control and drag compensation, the key elements for mission performance, achieved their mission flawlessly.

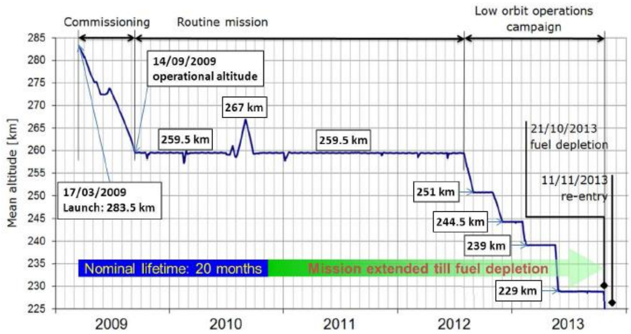

Fig. 1. GOCE altitude profile.

The two-domain (active/passive) thermal enclosure provided the gradiometer with 10 mK thermal stability over 200 s time intervals, as specified. The ion thrusters proved extremely reliable, totalling ≈500,000 Ns impulse over more than four years of continuous operation in all environmental conditions. The much-feared "beam-outs" (sudden and temporary interruptions of the thrust) were extremely rare and always recovered without a hitch. Drag compensation in the direction of the motion exceeded its requirement by a factor of about 10 (Fig. 3), proof to the quality of the control design, the accelerometer sensors and the ion thruster actuators. The in-flight calibration of the gradiometer (Cesare, 2010) provided the expected improvements of the Gravity Gradient Tensor (GGT) measurements. Aided by this, by the longer lifetime and by the exceptionally low orbit altitudes, all the mission performance goals on the geoid height and gravity anomaly measurement accuracy were met or exceeded, in spite the random errors on the GGT were higher than specified above 10 mHz.

3. GOCE AOCS

3.1 AOCS requirements

An essential element for meeting the mission requirements was represented by the Drag Free and Attitude control. In its early design concept, the GOCE drag-free control encompassed six (attitude and orbit) degrees of freedom. This was intended to provide enhanced robustness vs. the uncertainty attached to both environment and gradiometer response. The corresponding design had two ion thrusters for active compensation of the main component of the drag and eight micro-thrusters for lateral drag and attitude control. For the latter task, micro-machined cold-gas thrusters were the first candidates, later replaced by Field Emission Electric Propulsion (FEEP) thrusters due to limited on board resources. In summer 2003 it became clear that also the readiness of the FEEP technology was not compatible with the planned launch date, even accepting a delay of two years. It was therefore decided to move to a four d.o.f. design using ion thrusters for in line drag control and magnetic torquers for attitude control, supplemented by on/off cold-gas thrusters for gradiometer calibration purposes. The GOCE design team rose to the challenge and rapidly effected a complete re-design of the satellite controls and their interfaces, which touched on practically all on-board sub-systems and -partly- their accommodation (Fig. 2 and Sechi, 2011).

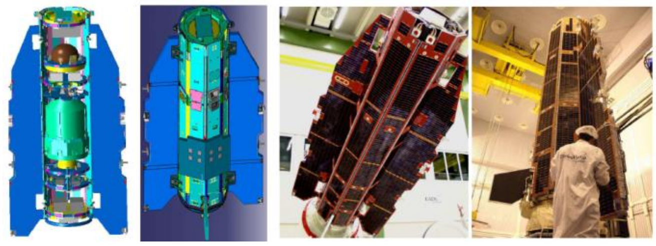

Fig. 2. GOCE configuration at the Critical Design Review (left pictures, May 2005) and at the Flight Acceptance Review (right pictures, March 2008).

By all standards, the GOCE Drag Free and Attitude Control (DFAC) has been an innovative design. Among its distinctive features, GOCE has been the first European drag-free mission, based on ultra-sensitive accelerometers, flying at a very low altitude, and it had the first pure magnetic attitude control system for a medium-sized Low Earth Orbit scientific satellite. The mission induced requirements not only on the magnitude of the residual disturbances, but also their spectral density in the science measurement bandwidth (MBW) of [5,100] mHz. To cope with such requirements, the payload measurements were fed to the control loop.

When in Drag Free Mode (DFM), DFAC had to ensure the limits reported in Tab.1, expressed both as maximum values in time and as maximum values of the square root of the unilateral spectral density inside the MBW. The requirements in Tab.1 are the final AOCS requirements after the GOCE control re-design. The relaxed requirements with respect to the original specs, did not affect the in-fight performances in spite of a more complex on-ground data post processing. The spectral density of the in-flight DFM linear acceleration performance (see Fig.3), has been computed considering one orbit (about 5400 s) of EGG measurements sampled at 10 Hz.

3.2 AOCS evolution: Magnetic Attitude Control

As mentioned, three Magnetic Torque Rods (MTR) were employed as the unique actuator for attitude, angular rate and angular acceleration control. The advantages of a fully magnetic control are a low actuation noise (fine command quantization levels are possible), a high reliability, and a low mass. Moreover, taking advantage of electro-magnetic field (EMF) intensity at the GOCE low orbital heights, small currents were sufficient to actuate the necessary control torques. The main problem was related to the reduced degree of controllability, because the MTR actuation system cannot produce a control torque along the EMF direction. Because of the GOCE quasi polar orbit, this direction rotated almost periodically in the orbit plane. This effect guaranteed an average controllability for the roll and yaw axes with a time horizon of half an orbit. The pitch axis was always controllable.

Table 1. DFAC DFM AOCS requirements

	Rotation axis	Max Value		Max PSD inside MBW	
Attitude w.r.t. LORF	Roll	0.15	rad	-	
	Pitch	0.06	rad	-	
	Yaw	0.15	rad	-	
Angular rate w.r.t LORF	Roll	$2\ 10^{-4}$	rad/s	10^{-5}	rad/s/√Hz
	Pitch	$0.3\ 10^{-4}$	rad/s	$5\ 10^{-7}$	rad/s/√Hz
	Yaw	$2\ 10^{-4}$	rad/s	10^{-6}	rad/s/√Hz
Angular acceleration	Roll	$1.8\ 10^{-6}$	rad/s^2	$0.9\ 10^{-7}$	rad/s^2/√Hz
	Pitch	$0.9\ 10^{-6}$	rad/s^2	$6.3\ 10^{-8}$	rad/s^2/√Hz
	Yaw	$0.9\ 10^{-6}$	rad/s^2	$6.3\ 10^{-8}$	rad/s^2/√Hz
Linear Acceleration (Along-track)		$0.9\ 10^{-6}$	m/s^2	$2.3\ 10^{-8}$	m/s^2/√Hz

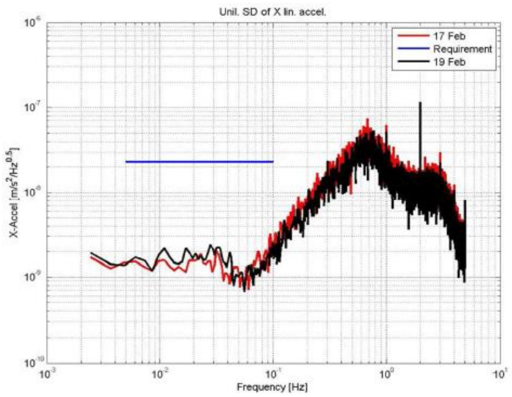

Fig. 3. Example of in-flight DFM linear acceleration performance. SD of the linear acc. in the direction of motion on 2 mission days (red, black) compared with the requirement (blue). The performance is ≈2×10-9 m/s²/√Hz all over the design MBW.

The reduced controllability leaded to attitude control performances that were linked to the dynamic disturbances. The satellite dynamics was dependent on the amplitude and phase of acceleration disturbances. The disturbances acting on the GOCE satellite were both induced by the environment (drag, gravity gradient, etc…) and by the platform (residual magnetic dipole and the ion thrust misalignments). The MTR instantaneous plane control capability has been complemented by a passive aerodynamic control, which was only effective in pitch and yaw. The aerodynamic passive control effectiveness were driven both by the distance between spacecraft Centre-of-Mass (CoM) and Centre-of-Pressure (CoP), and by the atmospheric density. This has led to a platform design maximizing the CoP-CoM distance by proper selection of the spacecraft mass distribution. A constant gain solution has been preferred for its simplicity and an inherent high degree of robustness. This has been also driven by computational constraints imposed by the GOCE on-board processor, by the wish to maintain as simple as possible the control algorithm architecture.

The following plots are relevant to the in-flight performance of the DFAC scientific mode attitude control. They have been obtained using the satellite telemetry: the time series are relevant to one day of data sampled at 50s, showing the compliance with margins shown in Tab.1.

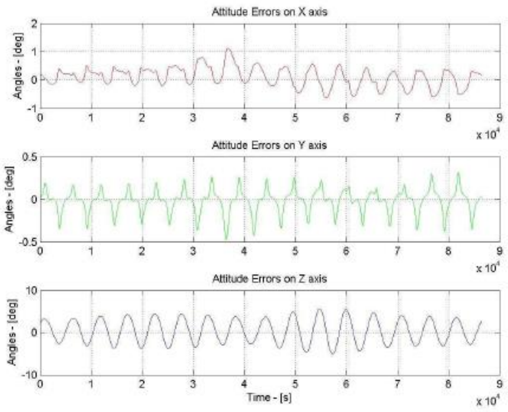

Fig. 4. Attitude control performance.

4. NGGM Mission Concept

After the successful mission GOCE, focusing on steady-state anomalies of the Earth's gravity field, the European Space Agency is proposing several preparatory studies for a future gravimetric mission. The main aim is the need of ensuring a proper continuity of gravity data to the scientific community, leveraging all the know-how gained through the GOCE and the US-German GRACE (and Follow-On) experience (GRACE URL). Hence, the Next Generation Gravity Mission concept was generated. Differently from GOCE, the NGGM mission objective aims at measuring the temporal variations of the Earth gravity field over a long time span (namely a full solar cycle). Such an objective will ideally enable the study of geophysical phenomena involving mass distribution and transport among the atmosphere, continental hydrosphere, oceans, cryosphere, and lithosphere, enabling new applications and observations at short and long time scales.

From the automatic control perspective, two major advancements can be defined, concerning both the technological level and the mission concept itself. Indeed, due to the NGGM mission objectives, some aspects of the automatic control, as the drag compensation, can be considered recursive between GOCE and NGGM. In that case the GOCE heritage will provide a reliable guarantee about the required level of performance; however, some major innovations can be expected, as an all-thruster configuration, ideally responsible for a fine controllability along and around all the spacecraft axes. From the platform perspective, the design developed so far envisages the opportunity of placing eight micro-thrusters, from micro- to milli-Newton range, placed all-around the satellite, Therefore, the GOCE drag-free design along the orbital motion axis, will be extended to all the three axes, both compensating the linear and the angular accelerations.

On the other side, given the wide range of differences in the NGGM mission concept with respect to GOCE, the automatic control system will be responsible of a totally new range of functions, like the formation and precise pointing. Indeed, the simplest mission scenario for NGGM consists of a single pair of satellites flying on the same orbit, with different true anomalies (“in-line” or “pearl string” formation). This in-line formation samples the gravity field in the along-track direction only. On a polar orbit, this formation is more sensitive to gravity field variations (and mass transport) in the North-South than in the East-West direction. Therefore, a second pair of satellites must be launched in conjunction with the polar orbit pair, operated in non-sun synchronous orbits to fill in, as much as possible, the polar cap. According to this approach, the gravity field can be sensed through the combination of the satellite pairs, flying in loose formation. Hence, an orbit and formation control is now required to counteract bias and drift of the residual drag-free accelerations, in order to reach a bounded orbit/formation long-term stability. As a consequence, the time variable gravity field signal shall be retrieved via the precise measurement of the inter-satellite distance variations induced by the gravity anomalies, through the low Earth orbit satellite-to-satellite tracking (SST) technique, as displayed in Fig. 5. On the other side, similarly to GOCE, an accelerometer suite, on each satellite, is intended to measure the non-gravitational accelerations induced by the atmospheric drag, which are used in the drag-reduction close loop, and then subtracted by the laser ranging measurement (converted consistently into accelerations) to retrieve the gravity signal, at data processing level.

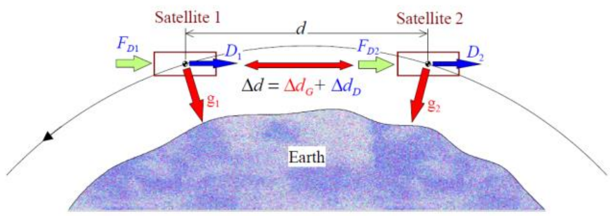

Fig. 5. NGGM satellite-to-satellite tracking concept.

The satellite-to-satellite tracking technology, with the need of an ultra-precise ranging control among the spacecraft, is a major GNC design driver. Specifically, one of the main challenging control requirement concerns the non-gravitational CoM accelerations, both linear and angular, as they must be ideally brought to zero. On the other side, the requirements concerning the orbit and formation control can be derived in order to counteract the differential effects of the drag-free control residual, which make the satellite formation diverging. Therefore the formation control, even if loose and not strictly maintaining the formation at sub-cm accuracy level during science phases, needs as inputs the real time positions of the leader (or alternately, of the follower) satellite, exchanged via an inter-satellite link (see Bacchetta, 2014 and Massotti, 2011). Finally, the attitude and pointing control system is intended to keep aligned the satellite optical axis and to eventually ensure an orbital roll motion for tracking the Sun beam (Canuto, 2015b).

Table 2. NGGM mission requirements

Performance variable	Bound	Unit
<u>Drag-free control</u>		
CoM acceleration (PSD in MBW)	0.01	$\mu m/s^2/\sqrt{Hz}$
CoM acceleration residuals	1	$\mu m/s^2$
<u>Orbit and formation control</u>		
Formation distance variation	5	% (distance)
Formation lateral variation	1	% (distance)
Formation radial variation	2	% (distance)
<u>Attitude and Pointing Control</u>		
Satellite X-axis pointing along the SSL	2	$\mu rad/\sqrt{Hz}$
Satellite X-axis roll along the SSL	2	mrad

The Table 2 lists the main requirements driving the automatic control design, in the science mode of the NGGM mission. Note that the formation requirements have been split into distance, radial and lateral variations with respect to a nominal circular orbit, expressed as a percentage of the nominal inter-satellite distance. It is very important also to stress that the most stringent requirements apply in the science measurement bandwidth [1,100] mHz, extended at lower frequency with respect to GOCE.

5. NGGM AOCS design

The AOCS for NGGM is an innovative design, conceived in a holistic way including, for the first time in Europe, an automatic (and not operated by the flight operations on ground) formation control for an Earth Observation satellite pair in low orbit. As a matter of fact, the AOCS is in charge of several control tasks, via a wise separation in the MBW: orbit altitude control, satellite formation control, drag-free and satellite-to-satellite pointing control. Specifically, the formation control must constrain the relative position of the two satellites, without interfering with the scientific measurements and the drag compensation (from where it is defined as a "loose" formation control). Conversely, the non-gravitational acceleration control of each satellite must operate without affecting the formation control and pointing capabilities.

The control architecture and logic consists in several control loops hierarchically organised (Fig. 6). Such multi-hierarchical control leverages an attitude and formation outer loop, which provides the long-term reference accelerations to be tracked by each individual drag compensation (or, simply, the so called drag "free") control. As anticipated, the control tasks operate in different frequency bands in order to manage -in a coordinated way- all the necessary controllers (satellite formation, orbit control, drag compensation and the satellite attitude/laser beam pointing control).

The attitude and formation are intended to be decoupled and all the coordinates are decomposed, so to have several SISO loops to be controlled separately. This design choice is also favoured by the choice of the control design methodology (i.e. the Embedded Model Control, see Canuto, 2014) and a mrad alignment between control frame and orbital, since the early mission phases, before the science control mode activation. However, such decoupling and decomposition do not completely apply to the formation and orbit mode, due to the altitude and distance modelling (typical of the Clohessy-Wiltshire-type equations, which show a coupling between in-line and radial equations). Therefore, an innovative approach was pursued to multi-satellite formation and orbit control based on their integration through the formation triangle virtual structure and the SSL line (Canuto, 2015a). The SSL line is defined as the vector connecting the CoM of the satellites, aligned with the first orbital axis, whereas the second orbital axis is orthogonal to the orbit plane and the third one completes the right-handed triad. Another fundamental factor driving the control design is the thruster authority. Indeed, the current design envisages a fully automatic all-propulsion mission, but conversely to GOCE, since NGGM is flying higher and given also the improved technological level in electric propulsion (and expected products availability), the fully automatic control unit can leverage a thruster maximum authority of few millinewtons only, to be split among all the above-mentioned control tasks.

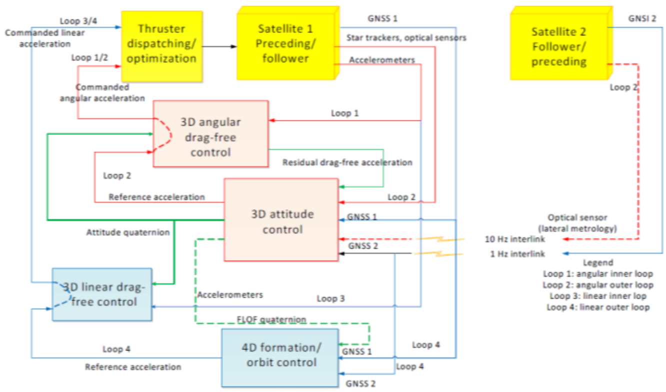

Fig. 6. AOCS overall block diagram.

The control algorithms, embedded in the box of Figure 6, are based on a discrete-time (DT) embedded model of the two-satellite formation kinematics and dynamics, based on the virtual structure of the formation triangle. As a consequence, the formation and orbit control, by controlling the average shape of this virtual structure, allows the satellites altitude and distance to be controlled in closed-loop. Such control actions are based on an integrated formation and orbit control law which is the combination of a feedback term and a disturbance rejection term. The feedback term injects back both formation position and velocity state variables. In addition, given a proper formation disturbance state observer, the disturbance rejection term allows the rejection of all the non-explicitly modelled dynamics (i.e. J2 effect, etc.) and the parametric uncertainty effects (see Colangelo, 2016).

Concerning the evolution of the automatic control design, it is worth to underline how, in a preliminary design phase, only the formation position variables were fed-back to generate the command. In the evolution of the control design, a formation rate damping control, operating at the time unit of the navigation data and damping suitably the formation rates, was added in order to bolster the formation stability (see Colangelo, 2016).

Focusing on the satellites attitude, the pointing control has to ensure the alignment of the satellites optical axis, to enable the measurement, via laser interferometry, of the inter-satellite distance variations, i.e. the scientific observables of such future gravity mission. The formation attitude rationale seeks an independent pointing control of each satellite, given proper optical sensors able to measure the satellite misalignments from the satellite-to-satellite line. The attitude kinematics and dynamics equations used in the control design are based on the definition of a proper attitude control reference frame, whose origin is in each satellite CoM, in addition to the other frames introduced up to now (Bacchetta, 2015).

A design aspect worth to be underlined, is the closed-loop tuning of the attitude state observers gains. As above mentioned, the pointing control must be coordinated with the angular drag-free control action. Hence, similarly to the linear case, the drag-free sets a frequency upper-bound to the pointing control action. Hence, a trade-off between the several pointing control objectives occurs. First of all, the control action must be able to cancel the accelerometer drift/bias at the low frequency band. Secondly, also the optical attitude sensor noises should be filtered at higher frequencies where they outnumber the accelerometer bound. Finally, the controller must ensure the closed-loop stability versus the attitude neglected dynamics. Specifically, the current tests and simulations show how the actual requirements set can be met without great margin (as shown in Figure 8), given the contrasting nature of the first two control objectives as described in Canuto, 2015b.

5.2 NGGM AOCS design: simulated results

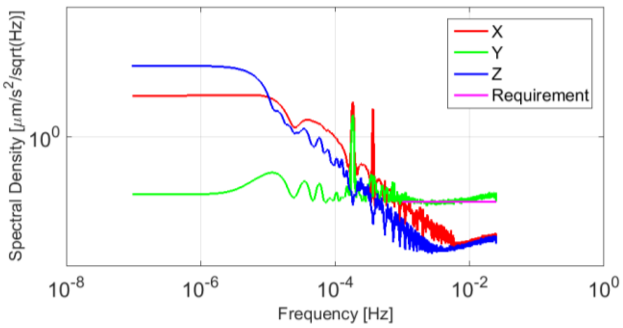

Fig. 7. Simulated linear residual acceleration performances.

In order to assess the control design validity as well as the NGGM AOCS performances, some relevant simulated results have been obtained through a high-fidelity E2E mission simulator. The science phase includes the linear and angular drag-compensation, attitude and pointing control and force/torque dispatching to a symmetrically-arranged eight-thruster assembly. From the environment perspective, the first 32 harmonics of the Earth gravity field spherical harmonics expansion have been simulated together with an Oersted geomagnetic field model (order 18) and min/mean/max solar activity conditions. Finally, all the sensor and actuator noises and dynamics are given as inputs to the simulations. The reference inter-satellite distance has been preliminary fixed to 200 km. From the control perspective, all the above mentioned controllers are considered in the closed-loop simulation.

Figure 7 shows the unilateral spectral density of the linear acceleration residuals versus the performance requirement. Such PSD has been computed on the whole residual profile including the transient, which explains the low-frequency overshoot.

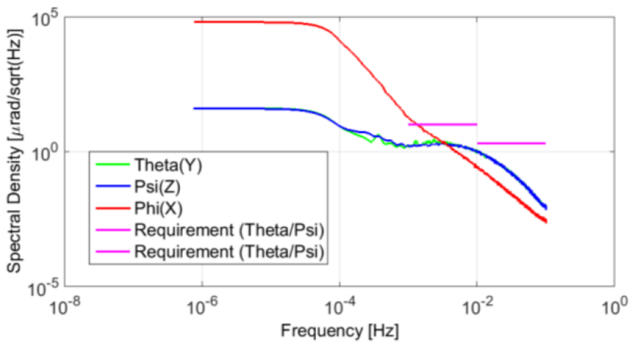

Fig. 8. Simulated attitude pointing performance.

In Fig. 8, the simulated PSD of the attitude tilt angles is presented. Both satellite pitch and yaw angles PSD (in green and blue, respectively) meet the requirement bound with some margin. For the roll angle (in red) a larger performance bound applies, not being the dynamics around the roll axis a constraint, since the laser interferometry measurements can be still performed accepting a larger roll angle, but given the satellite-to-satellite alignment requirements, as illustrated above (Tab. 2).

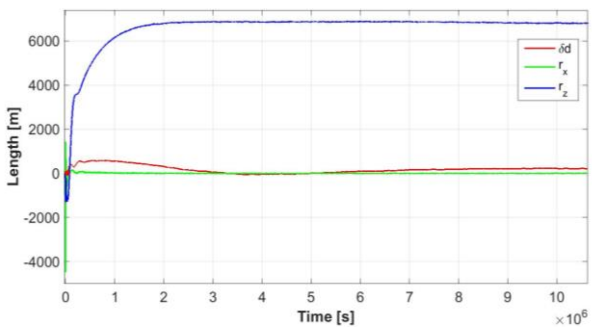

Fig. 9. Simulated attitude pointing performance.

Finally, in Fig. 9, the simulated formation triangle position variables time history (inter-satellite distance variation, in red, formation mean altitude, in blue, and formation mean radius deviation along the SSL) with respect to their reference values. All the formation variables are centred, on average, to their reference value as well their variation is within the bound that corresponds to the fractional requirement reported in Table 2. Hence, the designed loose formation control strategy appears to be able to bind the satellite formation drifting which would affect inter-satellite distance and formation altitude, due to the drag-free residuals effect.

6. CONCLUSIONS

This paper presents an overview on the attitude and orbit control systems conceived for two specific missions, devoted to the measurement of the gravity field at very low orbit. In particular the challenging linear drag compensation of GOCE has been reworked and extended to the 6 degrees of freedom of each satellite of the NGGM pair, where also a loose formation control enables an ultra-precise ranging measurement (at nanometre level) via heterodyne laser interferometry.

Acknowledgements

This study was carried out within the study "*Next Generation Gravity Mission (NGGM): AOCS Solutions and Technologies study*" funded by the European Space Agency, being Thales Alenia Space Italy (Turin, IT) the prime contractor, and Politecnico di Torino (Turin, IT) the subcontractor.

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